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13. ABSTRACT *(Maximum 200 words)*

Nondestructive damage evaluation theories to detect, locate and quantify damage in structures from vibrational characteristic measurements are summarized. Modal analysis experiments were conducted on cantilever beams and suspended plates using a laser interferometer vibration pattern imager. Resonant frequencies and mode shapes measured before and after damage were used to assess the inflicted damage. Three theories of damage detection were tested with the experimental measurements. It was found that the exact eigenvalue sensitivity method, which relates changes in eigenvalues and mode shapes to damage parameters, worked well in detecting the damage after an analytical model of the undamaged system was identified. However, the method was very sensitive to errors in the mode shape measurements. A method based on sensitivity of damage to eigenvectors required measurements of small changes of eigenvectors and was not proven. A modal strain energy approach, which culminated in an expression relating changes in thickness to changes in modal curvatures, is also summarized. Modal curvatures were obtained through curve-fitting and smoothing techniques. This method worked very well for cantilever beams but fail to conclusively detect damage in plates.

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DAMAGE EVALUATION OF STRUCTURES USING FREQUENCIES AND MODE SHAPES EXTRACTED FROM LASER INTERFEROMETRY

FINAL REPORT

by

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A. STATEMENT OF PROBLEM STUDIED

Background

The early detection of damage in structures is important for reasons ranging from safety to management of maintenance resources. Damage, in general, can be defined as undesirable weaknesses that risk the safety and performance of a structural system [1]. These weaknesses can come in the forms of cracks, delamination, bent members, broken or loose bolts or rivets, corroded members, reinforcement fracture, etc.. These forms of damage may be the results of overloading and/or environmental conditions. Many non-destructive methods already exist to detect some of these forms of damage. Among others, the following can be mentioned: visual methods, ultrasonic techniques, X-ray radiography, infrared thermography, acoustic holography, and stress waves methods. For the most part, these methods are very well developed and widely used. However, these are classified as local. This means that the inspections are limited to small portions of the structure.

Vibration methods are based on the fact that damage generally causes changes in the mechanical properties of the structural system, primarily stiffness. Since the vibration characteristics of structures are functions of these properties, then damage is accompanied by changes in these characteristics. Thus, in principle, if the resonant frequencies and mode shapes are measured before and after a damage, it is possible to solve an inverse problem to determine the changes in these mechanical properties (element stiffness and masses). These changes thus provide an indication of the location and magnitude of the damage.

Methods to extract vibrational characteristics of structures fall within the subject of Modal Analysis. These methods rely on experimental determination of frequency response functions between an excitation input and output responses. The excitation input is usually caused with electromechanical shakers and the responses measured with accelerometers. For the most part, these techniques only provide quantitative measurements of resonant frequencies and qualitative measurements of the mode shapes. Since all structures are continuous systems, and since the structures are usually sampled using few accelerometers, mode shape measurements are incomplete.

Objectives

The objectives of this project were:

(a) To develop a nondestructive damage evaluation theory to detect, locate and quantify damage in structures using changes of eigenfrequencies and eigenvectors measured with laser interferometry.

(b) Experimentally validate the damage evaluation theories for beam and plate-like structures.

The laser interferometer that was used for this investigation is the VPI 9000 manufactured by OMETRON. This laser unit is focused on the surface of a resonating structure. The position of the laser beam on the surface is controlled with moveable mirrors with a computer. The velocity signal and the excitation signal are passed through a correlator unit. This unit provides a DC output of the real and imaginary part of the velocity signal or the magnitude and phase of the velocity. These DC outputs are then passed to a data acquisition system where the data is permanently stored. The mirrors are then moved to another point on the structure and the data is acquired again. This process occurs at a rate of up to one hundred points per second.

B. SUMMARY OF MOST IMPORTANT RESULTS

Analytical Work

During the first year of this project, most of the efforts consisted of the development of damage detection theories that use changes of eigenfrequencies and eigenvectors. *Three theories were studied. The first one is called the eigenvalue* sensitivity method as reported in references [1] and [2]. The second is called the eigenvalue-eigenvector sensitivity method. And the third is the exact eigenvalue method. The last two theories were developed in this project. These theories are summarized in references [3] and [4].

The eigenvalue sensitivity method, when applied to a general viscously damped discrete system, uses a first order variation of the equation of motion to relate the changes of eigenvalues to changes of the structural matrices. The changes of the structural matrices are then related to damage variables that indicate the fractional changes of stiffness, mass and damping parameters. The damage parameters are dimensionless quantities that indicate the changes of the properties at a structural location. The method can be summarized with the following equation.

$$\{Z\} = [F]\{\alpha\} + [G]\{\beta\} + [H]\{\gamma\} \tag{1}$$

where, {Z} is a collection matrix of m fractional changes of eigenvalues, [F], [G] and [H] are m by n matrices containing eigenvalue sensitivity coefficients due to stiffness, mass and damping changes, respectively, in the n structural locations, and $\{\alpha\}$, $\{\beta\}$ and $\{\gamma\}$ are collection matrices of fractionalized stiffness, mass and damping parameters. The matrix {Z} can be experimentally measured. [F], [G] and [H] can be

obtained analytical from a model of the structural system. $\{\alpha\}$, $\{\beta\}$ and $\{\gamma\}$ are the unknowns that are solved using a least square pseudo inverse method.

The eigenvalue-eigenvector sensitivity method uses the equation above to relate the changes of eigenvalues to damage parameters but also uses expressions that relate the changes of the modes of vibrations (eigenvectors) to the same damage parameters. The equations that are introduced in this method are related to the partial derivative of eigenvectors with respect to structural parameters. For each quantifiable mode the following expression arises

$$\{Z_k\} = [F_k]\{\alpha\} + [G_k]\{\beta\} + [H_k]\{\gamma\} \qquad (2)$$

where, $\{Z_k\}$ is the change of the kth eigenvector, $[F_k]$, $[G_k]$ and $[H_k]$ are sensitivity matrices containing the kth eigenvector sensitivity coefficients due to stiffness, mass and damping changes, respectively. Theoretically, the matrix $\{Z_k\}$ can be experimentally measured using laser interferometry. As before, the sensitivity matrices can be obtained analytically from a model of the structural system. This method uses a combination of equations (1) and (2) to detect the damage.

The exact vibrational method was presented in references [3 and 4]. This method considers the changes in eigenvalues and eigenvectors due to damage. However, the damage prediction equations consider the changes of the orthogonality conditions due to the damage. The formulation can be represented in a similar form as equation (1). The method requires that, for each eigenfrequency, the corresponding mode shape be measured in the damage state.

The three damage detection theories discussed here were presented and extensively discussed in references [3, 4 and 5]. The three formulations were implemented in FORTRAN programs based on the finite element method. These programs require a finite element description of the undamaged system. Then, from the element stiffness, mass and damping matrices, the corresponding sensitivities due to damage are computed. From the input of the fractional changes of eigenvalues and changes of eigenvectors, the damage magnitude and the locations of damage are computed. The three formulations were subjected to a series of numerical experiments were damage was simulated via analytical models. Beam and plate models were considered. The damage consisted in reduction of stiffnesses at one and several locations. In all cases, the damage was accurately predicted.

The following findings can be mentioned:

1) The eigenvalue sensitivity method provides the best predictions when only frequency information is available. However, the resolution of the locations is limited by the number of resonant frequencies available.

2) The eigenvalue-eigenvector sensitivity method works extremely well using only one frequency and the corresponding mode shape. However, the computation of the sensitivities of damage on the changes of eigenvectors is tedious and computer intensive. It was realized, that for this method to work in actual scenarios, extremely small changes in the mode shapes needed to be measured. The laser interferometry at UTEP was not capable of delivering such accuracy.

3) The exact eigenvalue sensitivity method proved to be the most effective for prediction of damage in analytical models. This formulation was also tested using the changes in the eigenfrequencies and assuming that the changes of eigenvectors were zero. This was done using an iterative method. The location and the magnitude of the damage was always predicted with this method.

<u>Experimental work</u>

Most of the activities of this project were related to experimental work. During the first year of the project, modal analysis testing were performed on cantilever beams using conventional impact hammers and accelerometers. The laser interferometer scanning unit was delivered to UTEP at the beginning of the second year. Because funds were only available to purchase the basic system offered by OMETRON, significant modifications were done to the software that acquires the appropriate mode shape data. The software program that controls the experiments was modified in the following ways. 1) A subroutine was incorporated to control a signal generator. This was required to implement a swept sine method in search of the resonant frequencies. 2) The software as delivered did not measure the imaginary part of the velocity. This was essential to find the resonant frequencies, or the frequency of zero imaginary part. Thus, the software was modified to acquire the imaginary output from the correlator unit. 3) The controller consisted of a Hewlett Packard computer, model 332, with the HP Basic operating system. Such computer was not user friendly and modifications were performed to the software to export the data to the PC environment through a serial connection. Furthermore, the laser instrument was not simple to use and a great amount of time was devoted to training the scientific personnel to use it.

The work done by Martin Vila was primarily based on developments of the damage detection theories[5]. He carried out the analytical verifications of the theories and attempted to verify them using data from cantilever beams. He used 40-in. long aluminum beams. Resonant frequencies and mode shapes were acquired via impact testing before and after damage was inflicted. The cantilever beams were divided in 10 locations for the purpose of detecting damage. Damage consisted of introducing a saw cut at the middle of a location (one-tenth the length of the beam). He considered six different damage scenarios. Vila demonstrated that the eigenvalue sensitivity method and the exact eigenvalue method located the inflicted damage. In both cases the magnitude of the inflicted damage was not predicted but was in the

same order of magnitude as the actual values. Vila did not consider the eigenvector sensitivity method because quatifiable mode shape data was not available.

This work was then expanded by Nataraja Siddappa [6]. Siddappa was the first student to use the laser instrument to acquire mode shape data and to use that data to detect damage. Siddappa considered double-cantilever beam specimens attached to an electro-magnetic shaker. The procedure he used to find the resonant frequencies was to adjust the knob of a signal generator while observing the response in an oscilloscope. He considered three damage scenarios. The damage was caused by symmetrically reducing the depth of the beam by 15 percent over one-tenth the length of the beam. He collected 14 modes and frequencies before and after the damage was inflicted in each of the three beams. Each mode shape consisted of an array of 236 measurements along the length of the beam by 8 measurements across the width. After collecting the mode shapes, it was noticed that the vibrational images presented "speckle noise" caused be small imperfections on the surface of the specimens. These imperfections cause the laser beam to refract away from the optical sensor at the laser head. This causes smaller amplitude readings that the actual ones. It was also noticed that there was a shift in the lines of the data caused by the sequence of scanning. The laser scans left to right and then, right to left. On a transverse mode of a beam the lines of data do not match. In other words vertical nodal lines do not match between the odd lines and even lines. This problem gives the images a brick-wall appearance. Siddappa corrected the data by first taking the median value of the mode shape across the width of the beams. Secondly, the mode shape data was curve-fitted using cubic splines, replacing the values of outlier points. He used the mode shape and frequency data to test the exact eigenvalue sensitivity method. This method was tested two ways. First, the formulation was used using the mode shape measurements. Second, the formulation was used assuming that the changes of eigenvectors are zero and then let the solution scheme iterate updating the eigenvectors. He found that the damage detection results obtained from the exact eigenvalue sensitivity method are very sensitive to errors in the mode shapes. The results obtained by the iteration method detected the correct location and magnitude of the damage. He concluded that the laser instrument is extremely useful for the identification of a mathematical model of the undamaged structure. In other words, once a model has been identified that closely behaves with the same vibrational characteristics of the actual undamaged system, mode shape measurements are no longer needed.

Cesar Carrasco's work [7] was a natural extension to Siddappa's findings. He concentrated in ways to improve the quality of the mode shape measurements. He implemented a piecewise fourth-order technique to eliminate outlier points and to smooth the data. With his smoothing technique, Carrasco was able to compute the slope and the curvature along the length of the beams. Carrasco considered that reductions of stiffnesses cause change in the modal strain energy distribution of the beam. He proposed an energy approach to detect damage using laser interferometry

data without the use of the damage detection sensitivity methods. From modal strain energy equations, expressions relating changes in the depth of a beam to changes in the modal curvatures were developed. He repeated Siddappa's experiments and computed the modal curvatures for the undamaged and damaged beams. Using this technique Carrasco was able to detect the location and compute the correct magnitude of the damage. Preliminary results of his findings were included in Reference [8].

Rosa Rodriguez [9] expanded the modal strain energy approach to plates. She considered a rectangular plate suspended from a frame being excited with a speaker. The speaker was placed few inches behind the plate. In essence, the plate was with nearly free edges. Twelve mode shapes and frequencies were measured for an undamaged rectangular aluminum plate. Plates of equal thickness were built by bonding to thin plates. Cavitations were included by blocking out the adhesive material over a circular area of the interface of the two plates. The plates with cavitations were considered as the damaged plates. Vibrational images of 240 by 76 points of resolution were obtained for the undamaged and the damaged plates. The vibrational images were corrected for the brick-wall effects and for the speckle noise. The correction of the brick-wall effect required the determination of nodal lines considering first the measurements obtained when the laser head scanned from left to right. Then the same nodal lines we obtained using the measurements when the laser head moved from right to left. From these nodal lines, the average shift of the horizontal lines was obtained. Furthermore, to smooth the data fifth-order polynomial surface functions were used as fitting functions over overlapping sections of the images. Outlier points were eliminated using the technique developed by Carrasco. Rosa Rodriguez presented a methodology for correcting vibrational images acquired with the laser interferometer. She concluded that large modal strain energy differences in the higher modes detect the presence of damage. Differences in the modal energies of the lower modes fail to detect the presence of damage. She also found that only few modes exhibit modal energy difference delineating the damage.

C. LIST OF ALL PUBLICATIONS

1. R.A. Osegueda, M. Vila, and S.K. Mahajan "A Modal Analysis Method for Locating Stiffness and Mass Changes in Structures." In Developments in Theoretical and Applied Mechanics, S.V. Hanagud, M.P. Kamat, and C.E. Ueng, Editors, Vol. XV, Georgia Institute of Technology, Atlanta, Georgia, U.S.A., 1990, pp. 333-340.

2. R.A. Osegueda and M. Vila, "Vibrational Methods for Damage Detection in Aircraft Structures." In MRCE Monographs on Materials and Processes, Non Destructive Testing on Aircraft Structures, The University of Texas at El Paso, 1990.

3. A. Sanchez, "Effects of Damage on the Vibrational Modes of a Composite Material Beam",in Proc. of 1991 MAES National Engineering Symposium, April 17-20, NASA Johnson Space Center, Houston, Texas, pp. 164-175.

4. R.A. Osegueda, N. Siddappa, and C.J. Carrasco, "Effects of Structural Damage on the Vibrational Mode Shapes Measured with Laser Interferometry", Presented in the Texas Section ASCE 1991 Fall Meeting, October 4, 1991, South Padre Island, Texas, Texas Civil Engineer, Texas Section ASCE, Aug/Sept 1991, pp. 35.

5. M. Vila-Assaff, "Evaluation of Vibrational Damage Theories for Structure," Master of Science Thesis, Civil Engineering Department, The University of Texas at El Paso, El Paso, Texas, May 1990.

6. N. Siddappa, "An Improved Damage Evaluation of Structures Using Vibration Data Measured with Laser Interferometry," Master of Science Thesis, Civil Engineering Department, The University of Texas at El Paso, El Paso, Texas, May 1992.

7. C.J. Carrasco, "Damage Detection in Beams using Modal Energy Estimates," Master of Science Thesis, Civil Engineering Department, The University of Texas at El Paso, El Paso, Texas, August 1992.

8. R.M. Rodriguez, "Modal Energy of Plates Using Laser Interferometry for Damage Evaluation," Master of Science Thesis, Civil Engineering Department, The University of Texas at El Paso, El Paso, Texas, December 1992.

D. LIST OF ALL SCIENTIFIC PERSONNEL

During this investigation the following students were employed by the project:

a) Martin Vila-Assaff. He was employed from September 1989 until May 1990. He graduated with the degree of Master of Science in Civil Engineering in May 1990. His thesis title is "Evaluation of Vibrational Damage Detection Theories for Structures."

b) Nataraja Siddappa. He was employed from Jan. 90 until Nov. 1991. He graduated with the degree of Master of Science in Civil Engineering in May 1992. His thesis title is "An Improved Damage Evaluation of Structures Using Vibration Data Measured with Laser interferometry".

c) Cesar J. Carrasco. He was employed from Sept. 1990 until Aug. 1992. He graduated with the degree of Master of Science in Civil Engineering in Aug. 1992. His thesis title is "Damage Detection in Beams using Modal Energy Estimates."

d) Rosa M. Rodriguez. She was employed from Jan. 1991 until Aug. 1992. She has completed the requirements for the degree of Master of Science in Civil Engineering and will graduate in December 1992. She has also completed her thesis titled "Modal Energy of Plates Using Laser Interferometry for Damage Evaluation."

e) Murali Adekishava. He was employed from September 1991 until Aug. 1992. He scheduled to complete his Master of Science degree in May 1993. His tentative thesis title is "Comparison of Analytical experimental Mode Shapes of Plates."

f) Mario Gallegos. He was employed from June 1991 and Aug. 1991. He is expected to complete the requirements for the degree of Master of Science in Electrical Engineering. His thesis title is Damage detection of structures using Neural Networks.

g) Alfredo Sanchez. He was not employed by the project but was sponsored by the NSF program Research Careers for Minority Scholars to participate in this project. He will graduate with the degree of Bachelor of Science in Civil Engineering in December 1992.

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1. Stubbs, N.S. "A General Theory of Non-Destructive Damage Detection in Structures", Structural Control, Proceedings of the Second International Symposium on Structural Control, University of Waterloo, pp. 694-713; July 1985.

2. Stubbs, N.S.; and Osegueda, R.A. "Damage Detection in Periodic Structures," In Damage Mechanics and Continuum Modeling, ASCE, New York, pp. 113-128; 1985.

3. R.A. Osegueda and M. Vila, "Vibrational Methods for Damage Detection in Aircraft Structures." In MRCE Monographs on Materials and Processes, Non Destructive Testing on Aircraft Structures, The University of Texas at El Paso, 1990.

4. R.A. Osegueda, M. Vila, and S.K. Mahajan "A Modal Analysis Method for Locating Stiffness and Mass Changes in Structures." In Developments in Theoretical and Applied Mechanics, S.V. Hanagud, M.P. Kamat, and C.E. Ueng, Editors, Vol. XV, Georgia Institute of Technology, Atlanta, Georgia, U.S.A., 1990, pp. 333-340.

5. M. Vila-Assaff, "Evaluation of Vibrational Damage Theories for Structure," Master of Science Thesis, Civil Engineering Department, The University of Texas at El Paso, El Paso, Texas, May 1990.

6. N. Siddappa, "An Improved Damage Evaluation of Structures Using Vibration Data Measured with Laser Interferometry," Master of Science Thesis, Civil Engineering Department, The University of Texas at El Paso, El Paso, Texas, May 1992.

7. C.J. Carrasco, "Damage Detection in Beams using Modal Energy Estimates," Master of Science Thesis, Civil Engineering Department, The University of Texas at El Paso, El Paso, Texas, August 1992.

8. R.A. Osegueda, N. Siddappa, and C.J. Carrasco, "Effects of Structural Damage on the Vibrational Mode Shapes Measured with Laser Interferometry", Presented in the Texas Section ASCE 1991 Fall Meeting, October 4, 1991, South Padre Island, Texas, Texas Civil Engineer, Texas Section ASCE, Aug/Sept 1991, pp. 35.

9. R.M. Rodriguez, "Modal Energy of Plates Using Laser Interferometry for Damage Evaluation," Master of Science Thesis, Civil Engineering Department, The University of Texas at El Paso, El Paso, Texas, December 1992.